BOND STRENGTH OF FRP REINFORCEMENT IN CONCRETE AT ELEVATED TEMPERATURE

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ABSTRACT: A study on the bond capacity of fibre reinforced polymer (FRP) bars in concrete at elevated temperature is presented. By understanding the effects of temperature on the polymer resin matrix and on the FRPs' tensile and bond properties, and by rationally optimising the placement and anchorage of the bars, FRP reinforcements may be designed as fire-safe alternatives to steel reinforcement for concrete. However, this requires an understanding of the critical issues for FRP that could cause structural collapse under service loads during fire. The investigation presented in this paper includes determination of the glass transition temperature (T_g) of two commercially available, FRP reinforcing bars using dynamic mechanical analysis (DMA) and differential scanning calorimetry (DSC). Reductions in bond strength of these FRP bars at elevated temperature are also presented using steady-state bond pullout tests. It is shown that bond strength reduces at elevated temperature in the region of the lowest T_g value, determined using various possible test methods and definitions. The presented data are useful in making rational assessments of the likely structural fire resistance of FRP reinforced concrete elements, and will be used in analysis and interpretation of upcoming large-scale fire tests on FRP reinforced concrete slabs.

1. Introduction and Background

The introduction of FRP bars into concrete construction is becoming commonplace due to numerous well-known benefits; notably resistance to corrosion, reduced concrete cover, and optimisation of slab thickness. However, severe code restrictions typically remain where fire resistance requirements must be met. In conventional reinforced concrete, the critical temperature of steel reinforcing bars is typically defined by a 50% reduction in their tensile strength (yield strength) (Bisby and Kodur, 2007). On this basis, the critical temperatures of FRP bars are likely to be much lower than for steel, due primarily to softening of the polymer matrix resins used in the FRPs' manufacture at temperatures near their glass transition temperature (T_g). Furthermore, when using steel reinforcement, the bond of the reinforcement to the concrete is predominantly mechanical, and only mildly sensitive to elevated temperature. The bond mechanism of FRP to concrete typically depends on the bar coating which is bonded in a secondary curing process and therefore relies on shear transfer through the surface adhesive; bond of FRP bars is thus more susceptible to damage at elevated temperature (Katz et al., 1999). This paper seeks to quantify bond strength reductions for FRP bars at elevated temperatures, and if possible to correlate bond strength reductions to the T_g response of the FRP materials under DMA testing.

2. Experimental Program

Two commercially available glass FRP bars are used in the current study; these are denoted as BPG and PTG and shown in Fig. 1. Bar BPG has a double helical wrap with a fine sand coating as its surface treatment, whereas bar PTG has only a coarse sand coating. The manufacturer-specified mechanical properties of the bars are shown in Table 1. The experimental program included characterisation of both FRP bar types at elevated temperature to determine their T_g values; this was accomplished by DMA and DSC and by applying various permissible T_g definitions for each test method (see Bakis et al. 2014).

Table 2 shows the significant and considerable variation in the obtained T_g values from various test methods using various definitions.

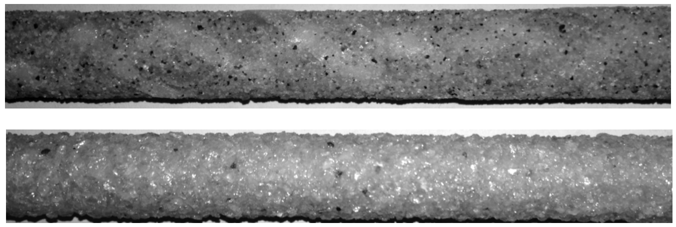

Fig. 1 – (a) Bar BPG and (b) Bar PTG

Table 1 – FRP bar properties.

Name	Manufacturer[a]	Size	Fibre Type	Fibre Content (% wt.)	Resin Type	Nominal Diam. (mm)	Min. Strength (MPa)	Mod. of Elasticity (GPa)
BPG	BP Composites	#3	Glass	83.6	Vinylester	10	1126	63.2
PTG	Pultrall	#3	Glass	83	Vinylester	9.5	889	53.4±2.5

[a] Specific commercial products are referred to only for the purposes of factual accuracy.

Table 2 – FRP glass transition temperatures.

	Glass Transition Temperature, T_g (°C)			
Specimen Name	T_g[a]	T_g[b]	T_g[c]	T_g[d]
BPG	86	108	136	149
PTG	84	108	153	156

[a] defined by the onset of storage modulus reduction (DMA testing)
[b] defined by peak rate of storage modulus reduction (DMA testing)
[c] defined by tan δ peak (DMA testing)
[d] defined by DSC differential (based on first notable thermal reaction)

Bond pullout tests were performed using 150 mm cubes of concrete (with a mean cylinder compressive strength of 27.5 MPa and a standard deviation 3.5 MPa) which were cast with embedded FRP bars; these were designed in accordance (to the extent possible given space limitations within the testing rig) with CSA S806-12 Annex H (CAN/CSA 2012). Prior to casting the samples a bond breaker was applied to the FRP bars, resulting in a bond length of only the central 40mm of the bar within the blocks. PVC tape was applied to the bar in two layers to create the bond breaker. Three thermocouples were embedded within each concrete block during casting to record bond-line temperatures during testing. Steel tubes were used to pot the free ends of the FRP bars with epoxy for gripping within the tensile testing frame. Tests were performed using an Instron 600LX frame with a built-in environmental chamber, and the samples were held inside the environmental chamber using a steel restraint cage. A photo of the test setup is given in Fig. 2.

Three tests were performed for each bar type at ambient temperature, and at least two steady state tests were performed for each type at elevated temperatures typically corresponding to the T_g values given in Table 2 for the respective bars. Given that the two uppermost T_g values determined for bar PTG were separated by only 3°C, it was decided to perform tests at slightly modified temperatures of 133°C and 153°C, to expand the range of tests performed.

Ambient temperature tests were performed by loading the sample to failure at a crosshead stroke rate of 2 mm per minute. Elevated temperature tests were performed by first loading the specimens to a nominal tensile bar stress of 10 MPa, to take up slack and to account for thermal expansion of the bars and the testing cage during the heating ramp. The environmental chamber was then programmed to ramp to a hold temperature 15°C greater than the desired steady-state test temperature, at a rate of 5°C per minute. The three thermocouples placed at the bar-concrete bond-line were used to monitor the progress of heating. When the desired temperature was reached at the surface of the FRP bar, the temperature within the environmental chamber was held for 15 minutes to promote even heating along and through the FRP bar. The specimen was then loaded under displacement control, again at a crosshead stroke rate of 2 mm per minute, until failure. Digital image correlation (DIC) analysis was also used to monitor bond slip at a rate of 0.2 Hz, however these data are not presented in the current paper.

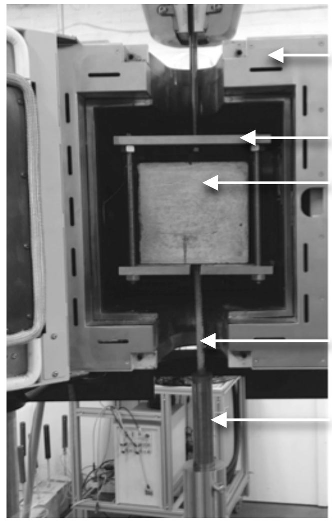

Fig. 2 - Photo Showing Bond Pullout Test Setup

3. Results and Discussion

Table 3 shows a summary of selected test data; average bond strength has been calculated using the peak tensile load (P_{max}), the bond embedment length (l), and the FRP bar nominal diameter (d) as shown in equation 1.

$$\tau = \frac{Pmax}{\pi dl} \tag{1}$$

It was expected that once the bond had failed, a descending branch in the bond stress versus stroke response would be observed; however, in many of the tests the specimen continued to carry increased load, beyond a distinct initial bond stress peak, at a much reduced stiffness. This response is thought to be due to the bond breaker not functioning as intended once the FRP-concrete bond had been lost, and additional tests are currently underway to confirm this hypothesis. Many of the tests at lower temperatures eventually failed by splitting of the concrete block; this was also unexpected and again is thought to be due to the bond breaker bunching and artificially enhancing bond strength by providing mechanical interlocking. It is proposed that plastic surgical tubing, with an internal diameter close to that of the FRP bar, would be a better solution for use as a bond breaker.

Despite the PTG bars being the comparatively weaker bar in terms of ultimate tensile strength, and despite both bars having similar T_g values when defined by most of the test methods and definitions given in Table 2, the bond test results suggest superior bond performance at all test temperatures (including ambient temperature). This could be due to the coarser grained sand coating, which appears to be the only differentiating factor that might lead to higher bond strength. It is important to note that in order to fully understand the influence of bar coating on bond performance at elevated temperature it will be necessary to learn more about resins and manufacturing techniques used in the secondary curing process used to apply the bars' coatings.

Ultimate failures of the specimens at elevated temperature transitioned from splitting of the concrete blocks to pullout bond failure with eventual separation of the bars surface coating from the bars. this is shown in Fig. 3 for the PTG bars as an example, and confirms that bond failure at elevated temperature (for these bars at least) is strongly dependent on the ability of the polymer coating to remain attached to the bars' surface (i.e. shear transfer through the resin at the surface of the bar). It is thus unsurprising that the reductions in bond strength correlate reasonably well with the storage modulus curves obtained during DMA testing, since storage modulus varies proportionally with both tensile and shear modulus for most polymer resins (refer to Fig. 5 where the DMA storage modulus curves have been included for comparison). This suggests that DMA testing could be used as a proxy test for bond strength reductions of FRP bars in concrete at elevated temperature.

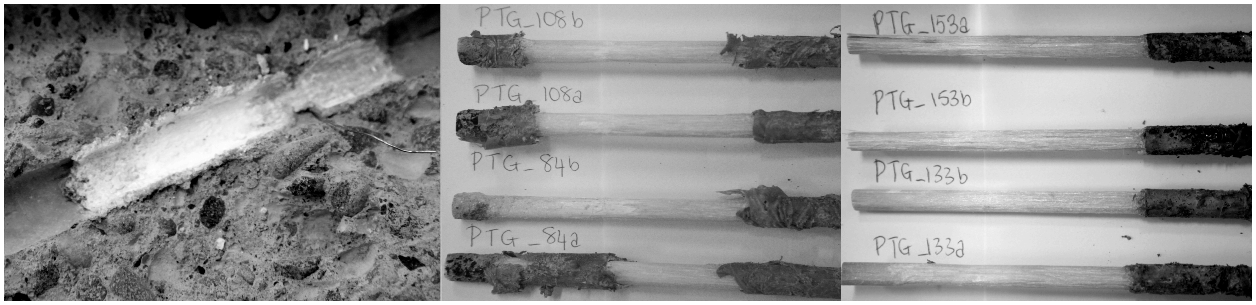

Fig. 3 - Residual Bar Coating (left) and Typical Bond Failures for Bar PTG (right)

Fig. 4 shows bond stress versus crosshead stroke curves for all tests performed to date (note the different vertical and horizontal scales used in the left hand and right hand plots), and Fig. 5 shows normalised peak bond stress versus test temperature. These figures, along with the data given Table 3, show that both bar types experienced severe reductions in bond strength at temperatures in the range of T_g, confirming results obtained previously by Katz et al. (1999) for various other glass FRP reinforcing bars. For instance, PTG bars experienced an 80% reduction in bond strength at T_g^d, whereas BPG saw a 60% reduction at similar temperatures.

Table 3 – Selected experimental results.

FRP	Test Temp. (°C)	Peak Load (kN)	Crosshead Stroke at Peak Load (mm)	Failure Mode	Peak Bond Stress (MPa)	
					Test	Average
BPG	25	12.8	2.8	Splitting	10.2	9.5
		12.4	2.5	Bar Pullout	9.9	
		10.8	2.2	Splitting	8.6	
	86	11.2	2.9	Splitting	9.0	5.1*
		6.7	1.9	Splitting	5.3	
		6.2	1.6	Splitting	4.9	
	108	9.3	2.4	Splitting	7.4	6.3
		6.6	1.6	Splitting	5.3	
	136	5.9	1.4	Bar Pullout	4.7	4.0
		4.1	1.3	Splitting	3.3	
	149	3.9	0.8	Bar Pullout	3.1	3.5
		4.9	1.3	Bar Pullout	3.9	
PTG	25	25.4	6.1	Splitting	20.2	21.0
		27.8	5.9	Splitting	22.1	
		26.0	5.6	Splitting	20.7	
	84	12.3	3.1	Splitting	9.9	9.3
		10.8	3.0	Splitting	8.6	
	108	9.2	2.2	Splitting	7.3	10.7
		17.7	4.2	Splitting	14.1	
	133	9.9	2.5	Splitting	7.9	7.0
		7.6	2.3	Bar Pullout	6.0	
	153	4.8	1.2	Bar Pullout	3.8	3.8
		Bar Pullout during heating				

*Excludes the peak bond stress of 9.0MPa due to the high variability in the results.

Fig. 4 shows that the load versus crosshead stroke response of the specimens was similar in all cases, aside from the obvious reductions in peak load already discussed. It is noteworthy that the curves have been truncated just beyond the initial peak bond stress for clarity of presentation; data beyond this point are not considered significant for the reasons already noted. The slope of the ascending branch of the load-stroke curves appeared to be mildly influenced by elevated temperatures, with slight bond stiffness reductions apparent at higher test temperatures. This may also be partly attributed to reductions in the tensile stiffness of the FRP bars themselves at elevated temperature; tests on the tensile properties of the bars themselves at various temperatures from ambient to greater than 300°C are underway.

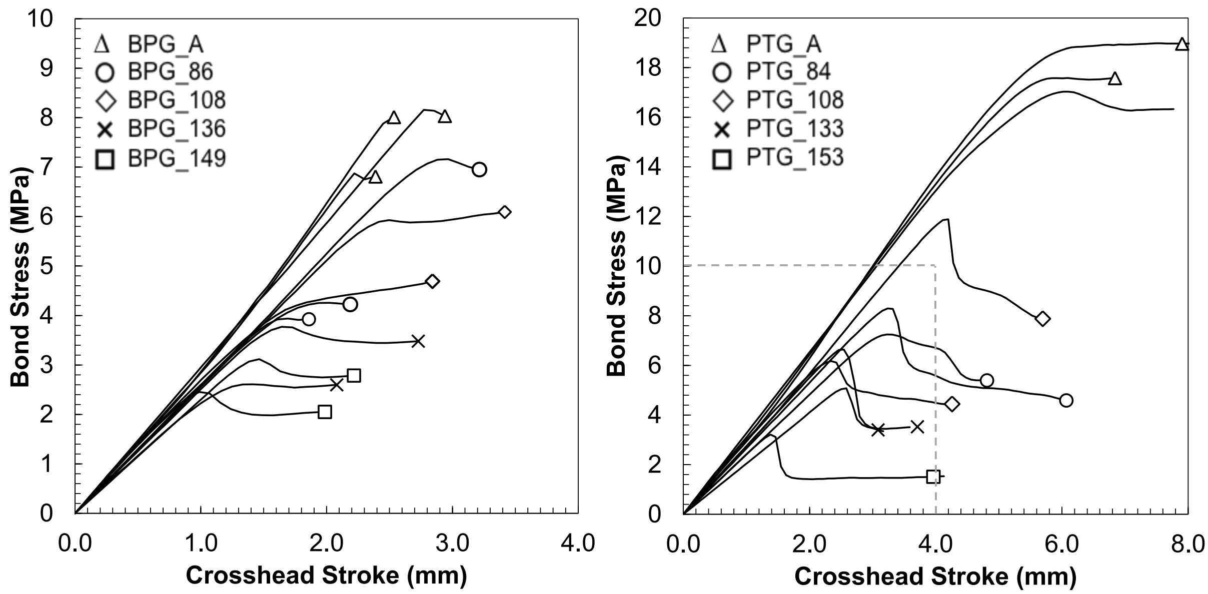

Fig. 4 - Bond Stress versus Crosshead Stroke (Left: BPG, Right: PTG)

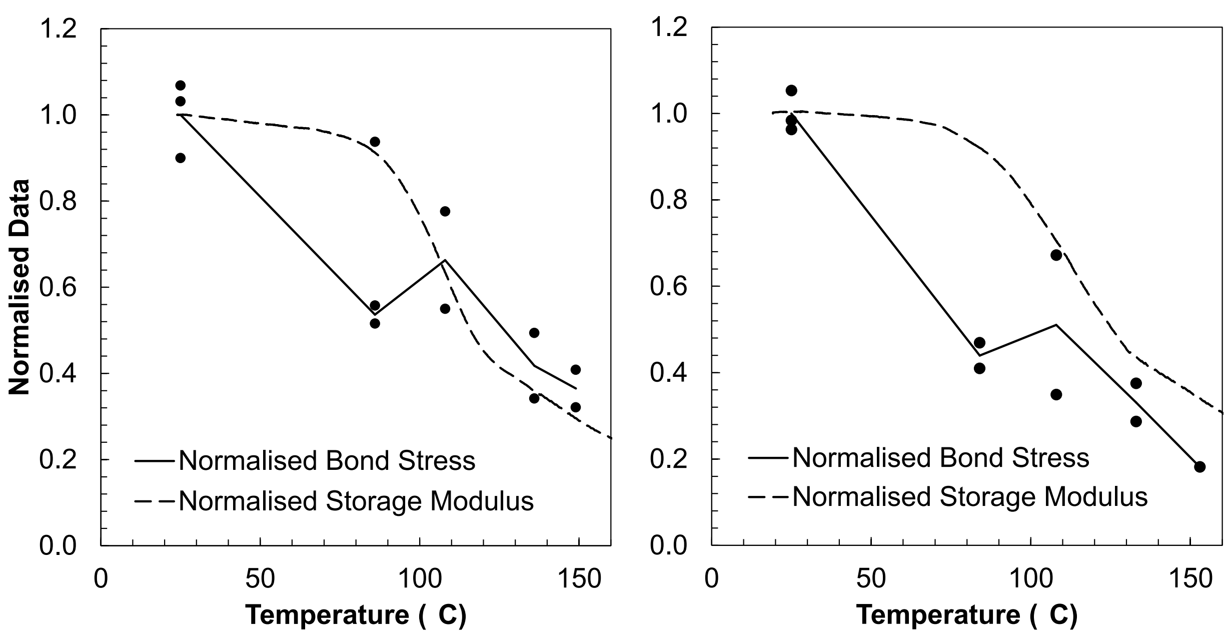

Fig. 5 - Normalised Bond Stress (Strength from Bond Pullout Tests) & Normalised Storage Modulus Curves (from DMA Tests) versus Temperature (Left: BPG, Right: PTG)

Considerable scatter was observed in the bond strength data (Fig. 5) and the reasons for this are not clear. The bond stress obtained for the first experiment on bar BPG at 86°C has been excluded from the average due to high variability in the results. As already noted the authors suspect that the bond breaker used in these tests may not have functioned as intended; additional tests are therefore underway to corroborate the data obtained to date.

4. Conclusions

Based on the experimental study of the bond of FRP bars in concrete at elevated temperature presented in this paper, it has been demonstrated that:

- the bond strength of FRP bars embedded within concrete decreases considerably as the temperature at the bond-line increases in the range of the bars' glass transition temperature (T_g); significant bond strength reductions are observed at temperatures corresponding to the lowest T_g defined for the bars on the basis of the onset of a reduction in the bars' storage modulus during DMA testing (i.e. T_g^a in Table 2);
- if maintaining the bond between FRP bars and concrete is critical for the performance of an FRP reinforced concrete element (as it would be in many cases), and if no cold anchorage zone can be assured, the temperature of the FRP reinforcement should be maintained at temperatures below the T_g^a value defined above; this would correspond to temperature limits of about 86°C and 84°C for the BPG and PTG bars tested herein, with an additional (as yet undetermined) safety factor included;
- the specific formulation of the FRP bars' coating material appears to affect the bond effectiveness (and bond capacity) at ambient and elevated temperature; however interestingly the normalized bond strength reductions experienced at elevated temperature appear to be similar regardless of the absolute ambient temperature bond strength; and
- bond strength reductions at elevated temperature correlate reasonably well to storage modulus reductions observed through DMA testing on the FRP bars themselves, suggesting that DMA testing could possibly be used as proxy testing for quantifying elevated temperature bond strength reductions for FRP bars in concrete; this could possibly eliminate the need to perform a large suite of costly and time consuming high temperature bond pullout tests on all new FRP bar products as they come to market; additional testing is required to confirm this concept.

5. Acknowledgements

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